Effects of the Observed Meridional Flow Variations since 1996 on the Sun's Polar Fields

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Key Points

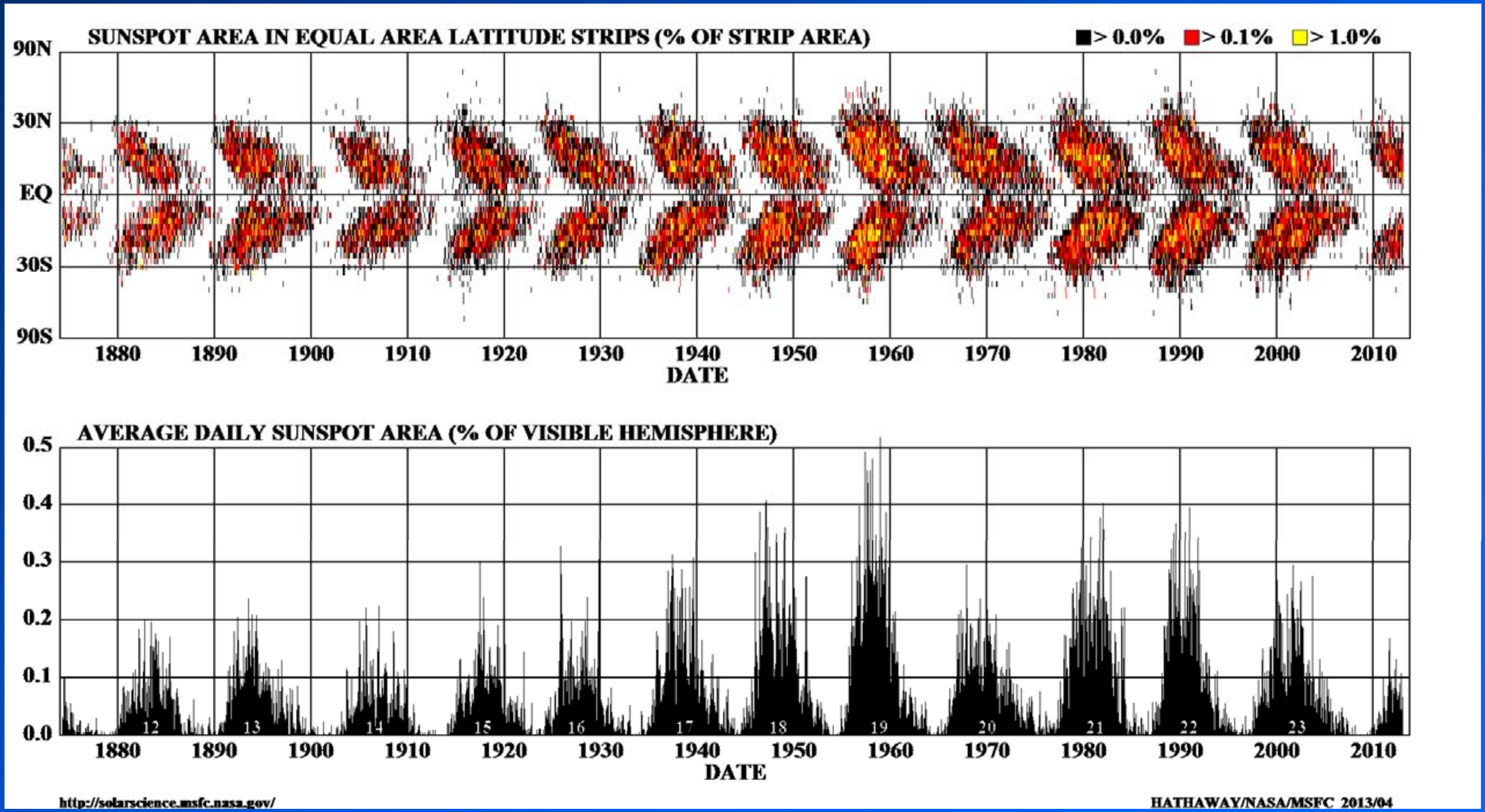
1. Polar fields at cycle minimum produce and predict the amplitude of the next cycle maximum

2. Polar fields are produced by the advective transport of fields from decaying active regions

3. Variations in the poleward meridional flow are the most likely cause of variations in the polar fields and solar cycle amplitudes

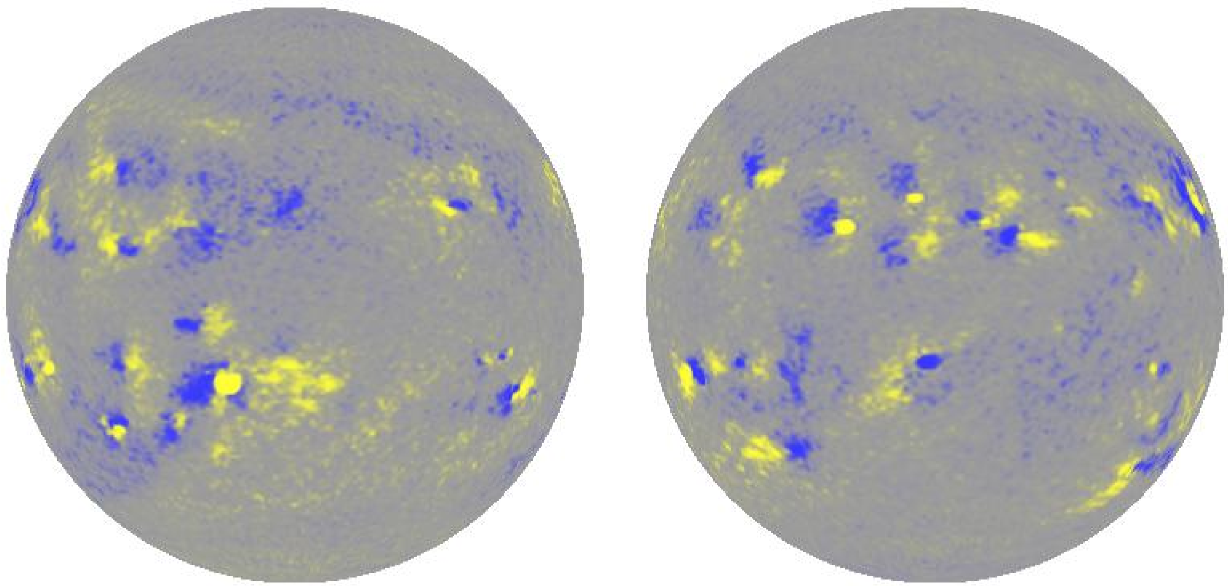
Sunspot Zones

Sunspots appear in two latitude zones, one in the north and one in the south. These zones drift toward the equator as each cycle progresses – following the same standard path without regard to cycle strength or changes in the meridional flow (Hathaway, 2011).



Hale's Law

In 1919 Hale (along with Ellerman, Nicholson, and Joy) found that the magnetic field in sunspots followed a definite law, "Hale's Law" such that: ***"…the preceding and following spots … are of opposite polarity, and that the corresponding spots of such groups in the Northern and Southern hemispheres are also opposite in sign. Furthermore, the spots of the present cycle are opposite in polarity to those of the last cycle".***

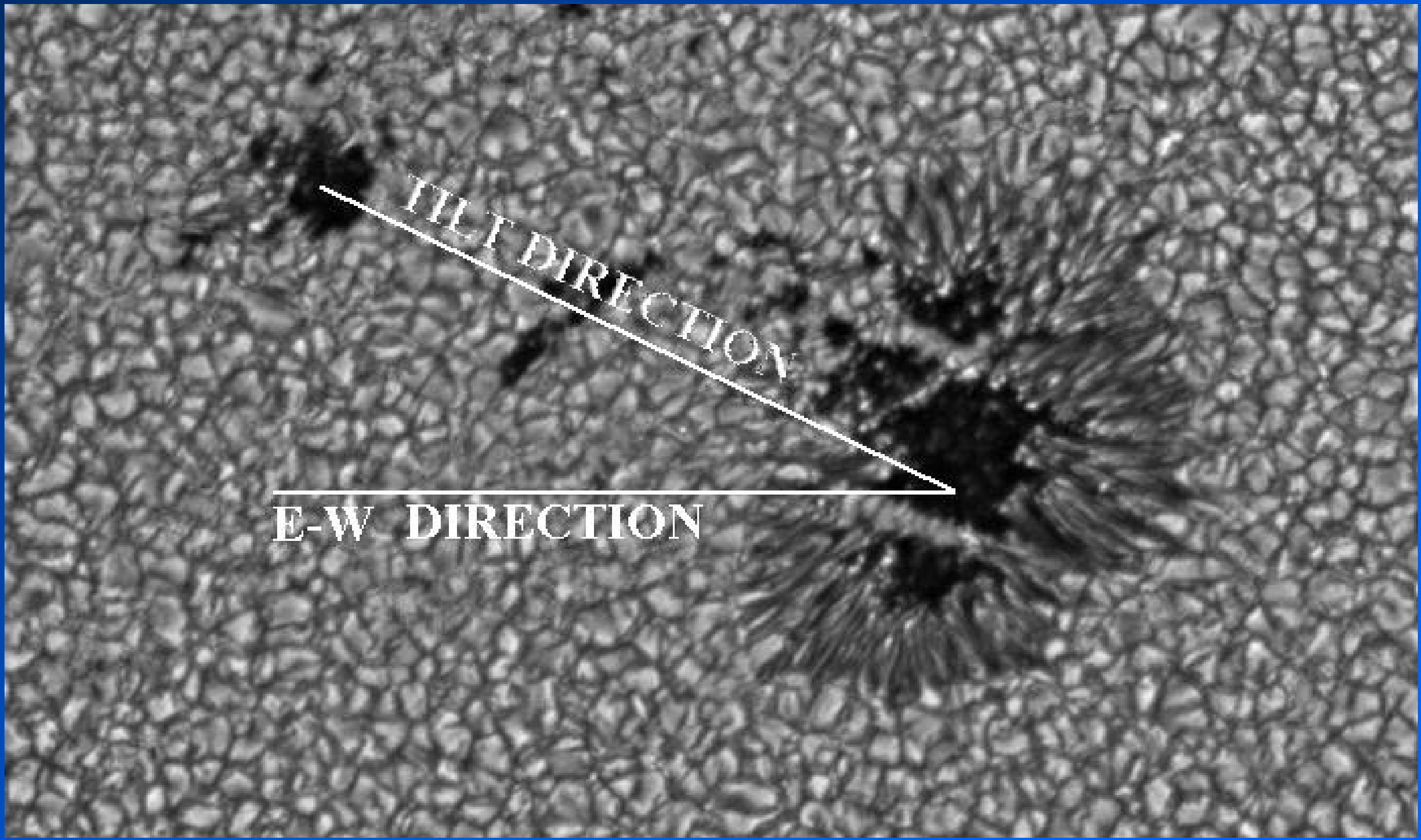


Cycle 22
1989 August 02

Cycle 23
2000 June 26

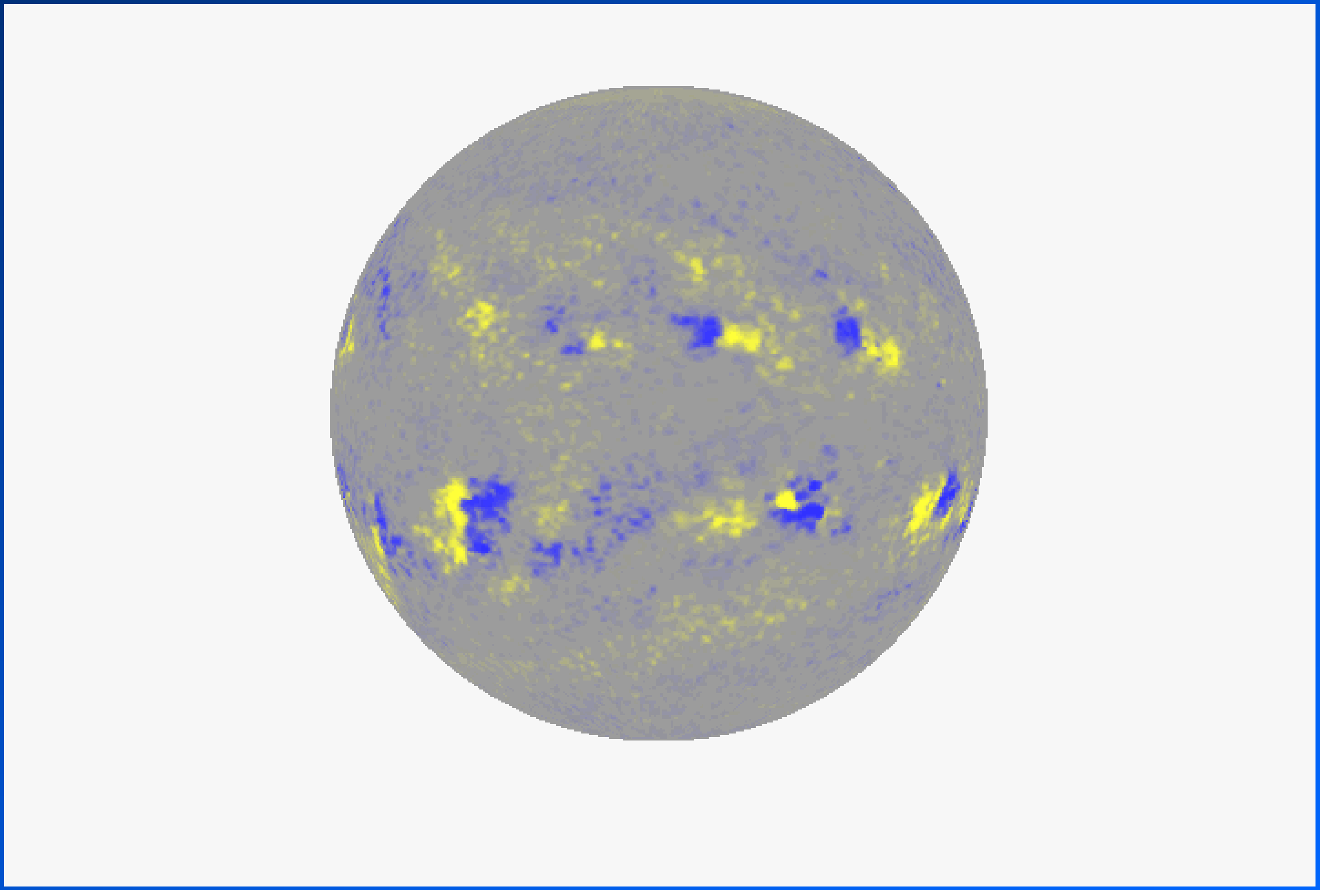
Joy's Law

In that same 1919 paper Joy noted that sunspot groups are tilted with the leading spots closer to the equator than the following spots. This tilt increases with latitude but is highly variable from sunspot group to sunspot group.



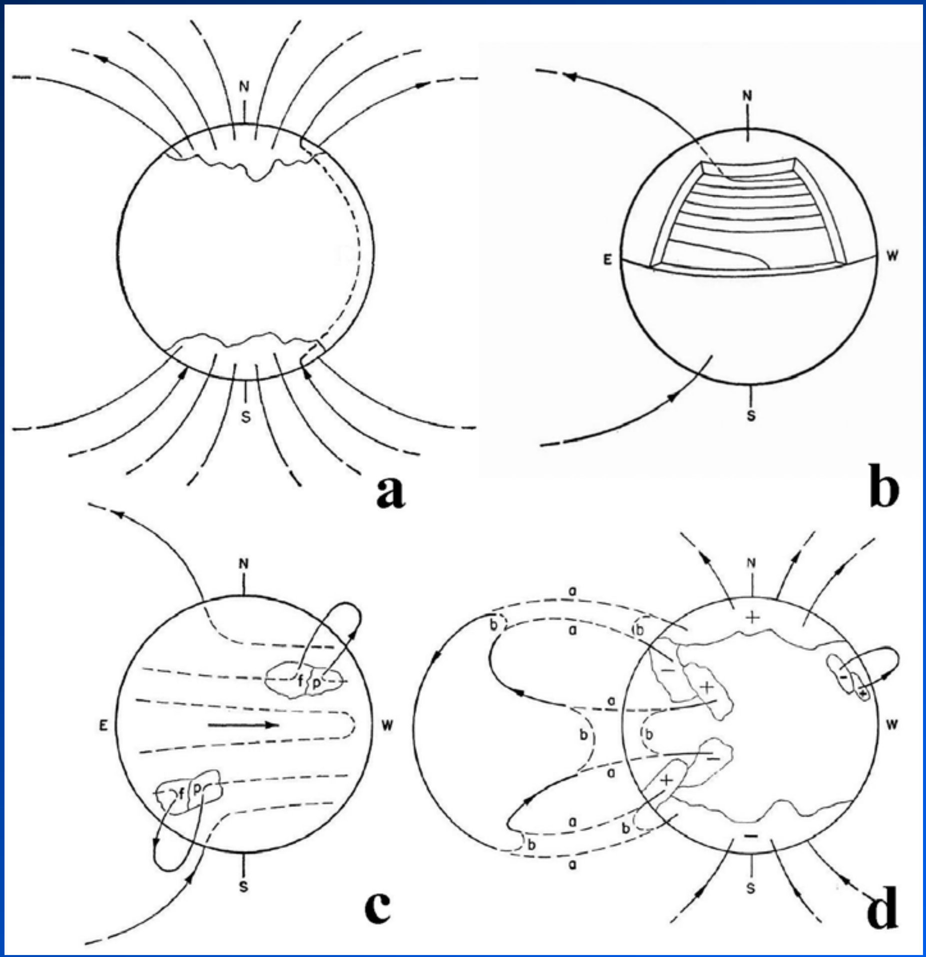
Flux Transport

Magnetic flux that emerges in active regions is transported across the sun's surface by differential rotation (drifting prograde near the equator and retrograde at high latitudes) and meridional flow (poleward from the equator).



The Babcock Dynamo (1961)

(son Horace , not father Harold)



a) Dipolar field at cycle minimum threads through a shallow layer below the surface.

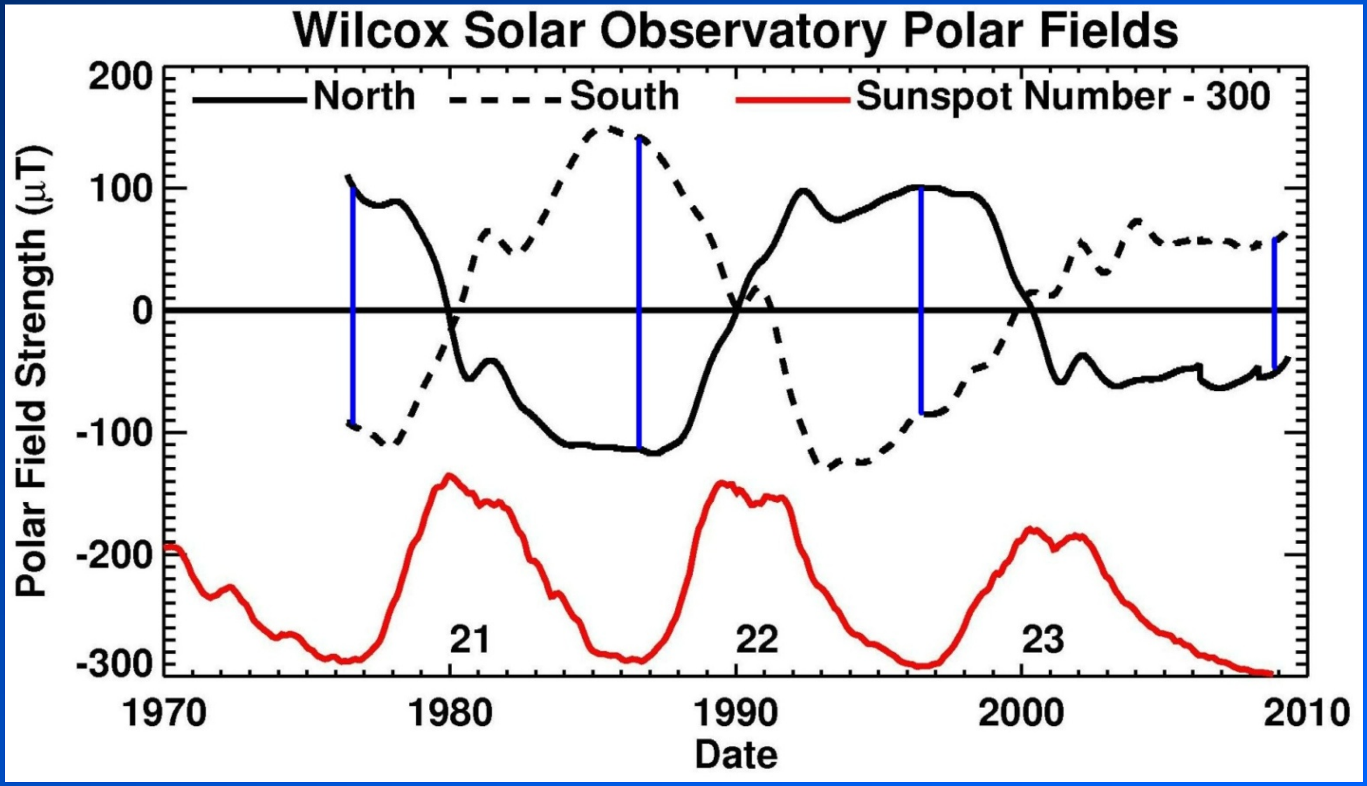
b) Latitudinal differential rotation shears out this poloidal field to produce a strong toroidal field (first at the mid-latitudes then progressively lower latitudes).

c) Buoyant fields erupt through the photosphere giving Hale's polarity law and Joy's Tilt.

d) Meridional flow away from the active latitudes gives reconnection at the poles and equator.

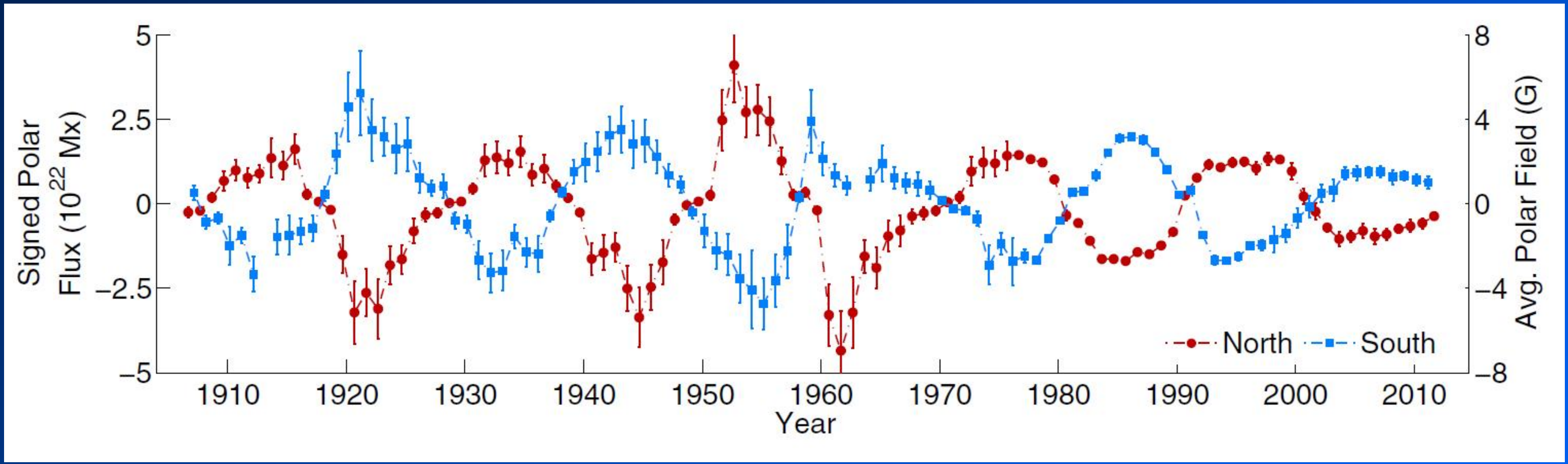
Polar Fields Prediction

In Babcock's model, and many more since then, the strength of the Sun's polar fields near the time of sunspot cycle minimum is the seed for the next solar cycle. Polar fields have been used to reliably predict the last three sunspot cycles.



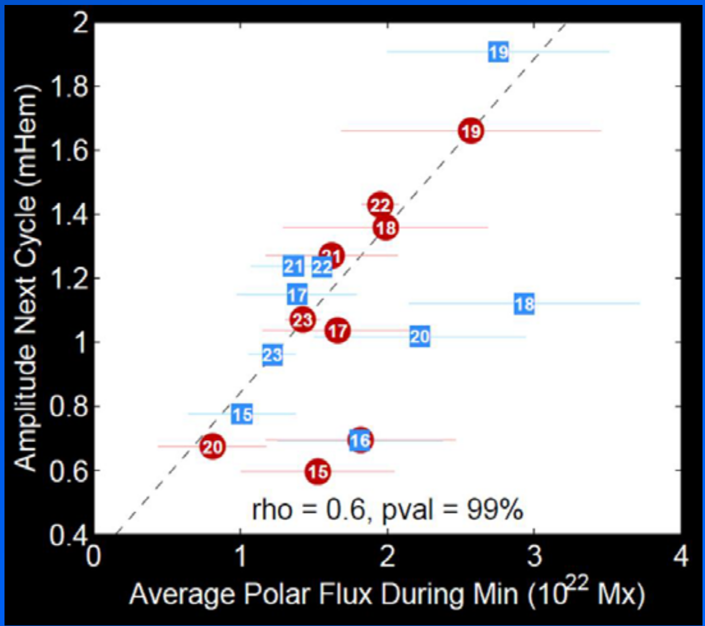
The weak polar fields at the last minimum indicate a Cycle 24 peak of 75±8 (Svalgaard, Cliver, & Kamide 2005).

Polar Faculae/Polar Fields

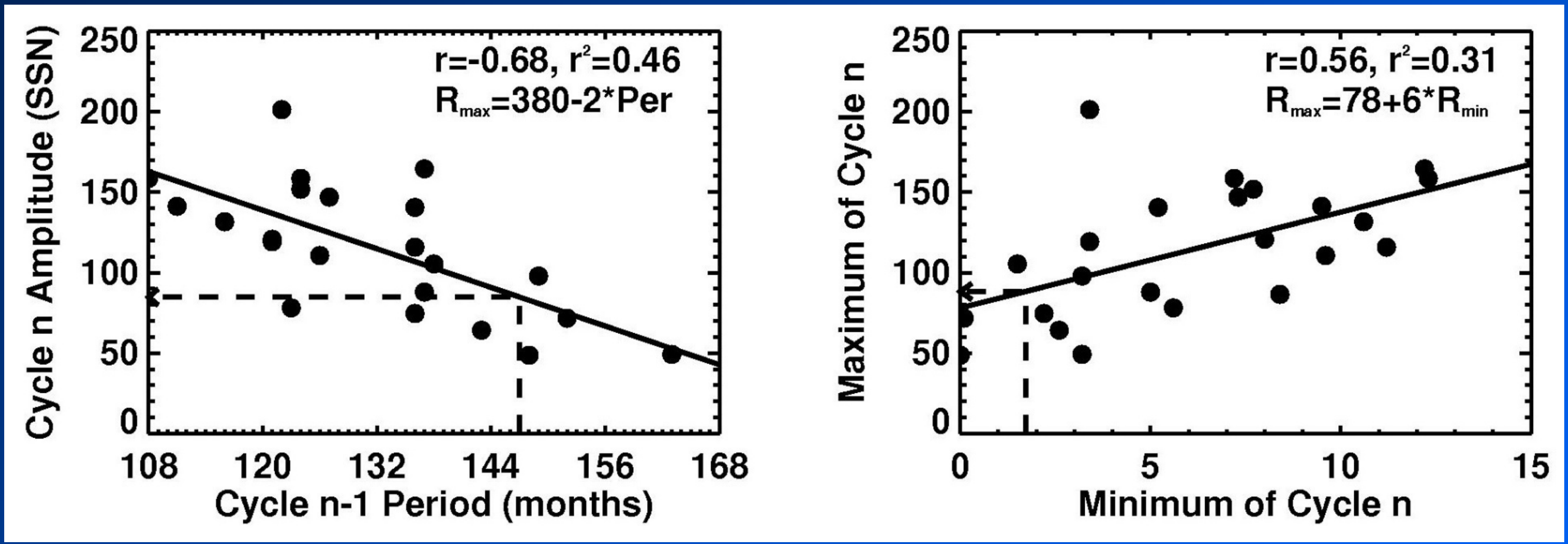


Recently, Muñoz-Jaramillo et al. (2012) showed that the (corrected) number of polar faculae seen on Mt. Wilson photographs by Neil Sheeley is a good proxy for polar field strength and flux.

The polar field at minimum is a good predictor of the amplitude of the next cycle .



(Weaker) Statistical Expectations



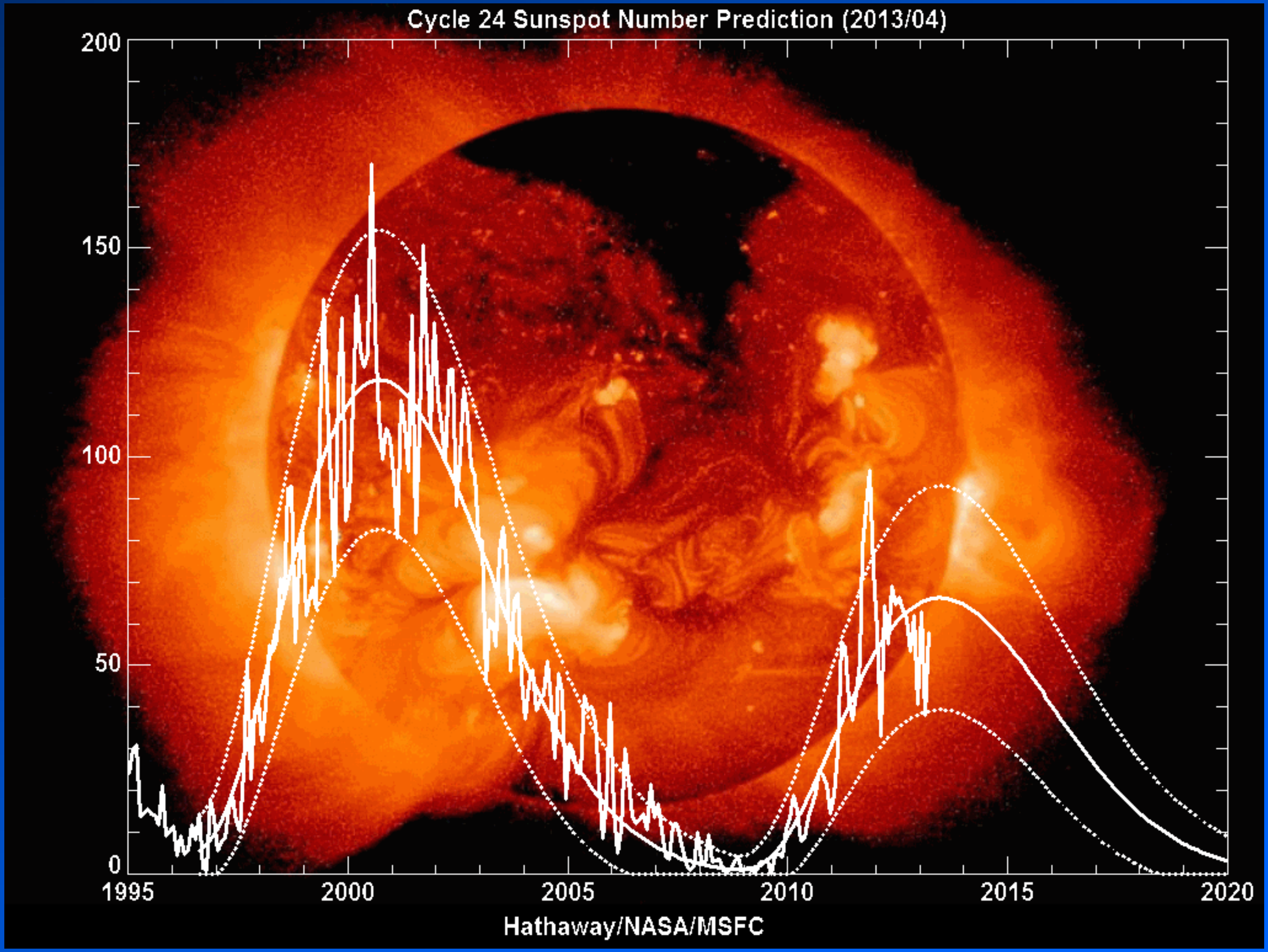
The last cycle was 147 months long – suggesting that Cycle 24 maximum will be **86±30**.

The sunspot number at Cycle 24 minimum was 1.7 – suggesting that Cycle 24 maximum will be **87±33**.

Typically, small cycles start late and leave behind a long cycle and a low minimum (Hathaway *et al.* 2002.)

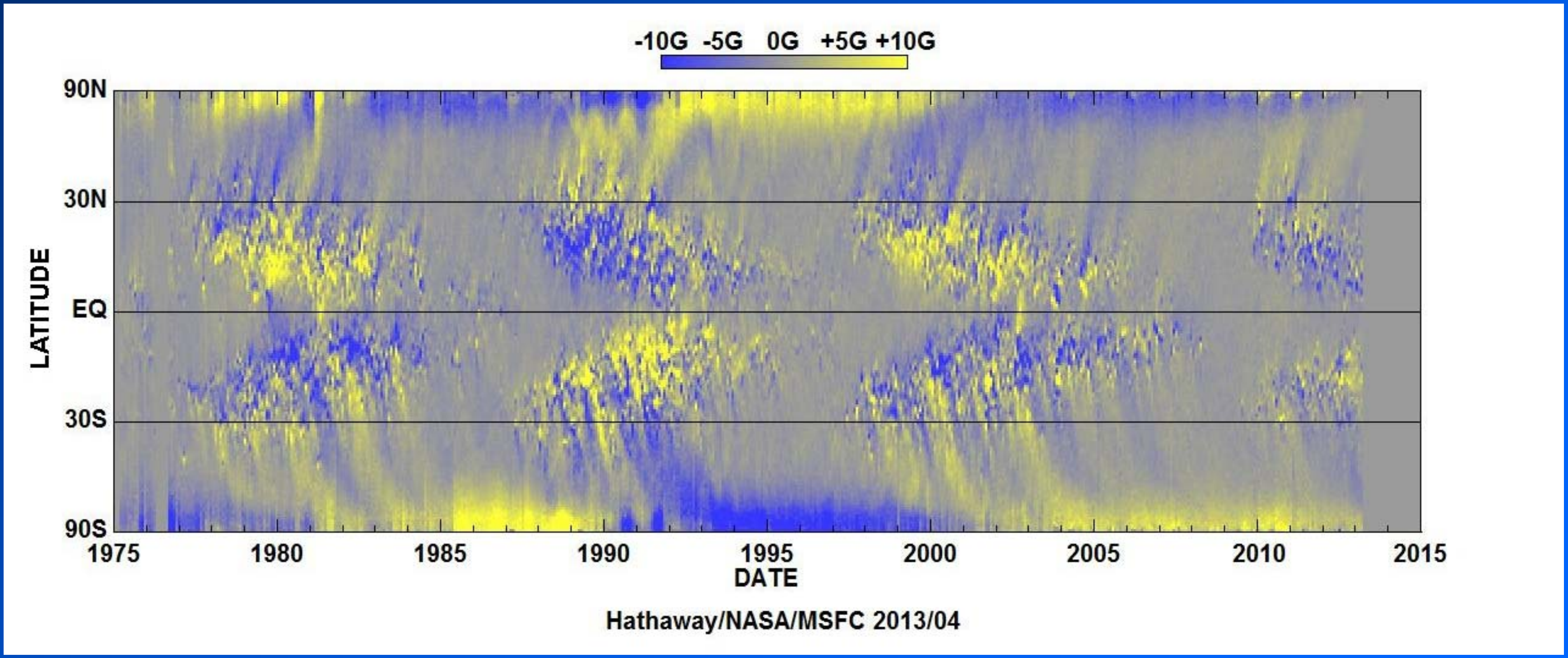
Cycle 24 Rise to (Mini) Max

Fitting a parametric curve (Hathaway et al. 1994) to the monthly sunspot numbers indicates peak sunspot number for Cycle 24 of ~66 – a weak cycle due to weak polar fields … but why were the polar fields so weak?



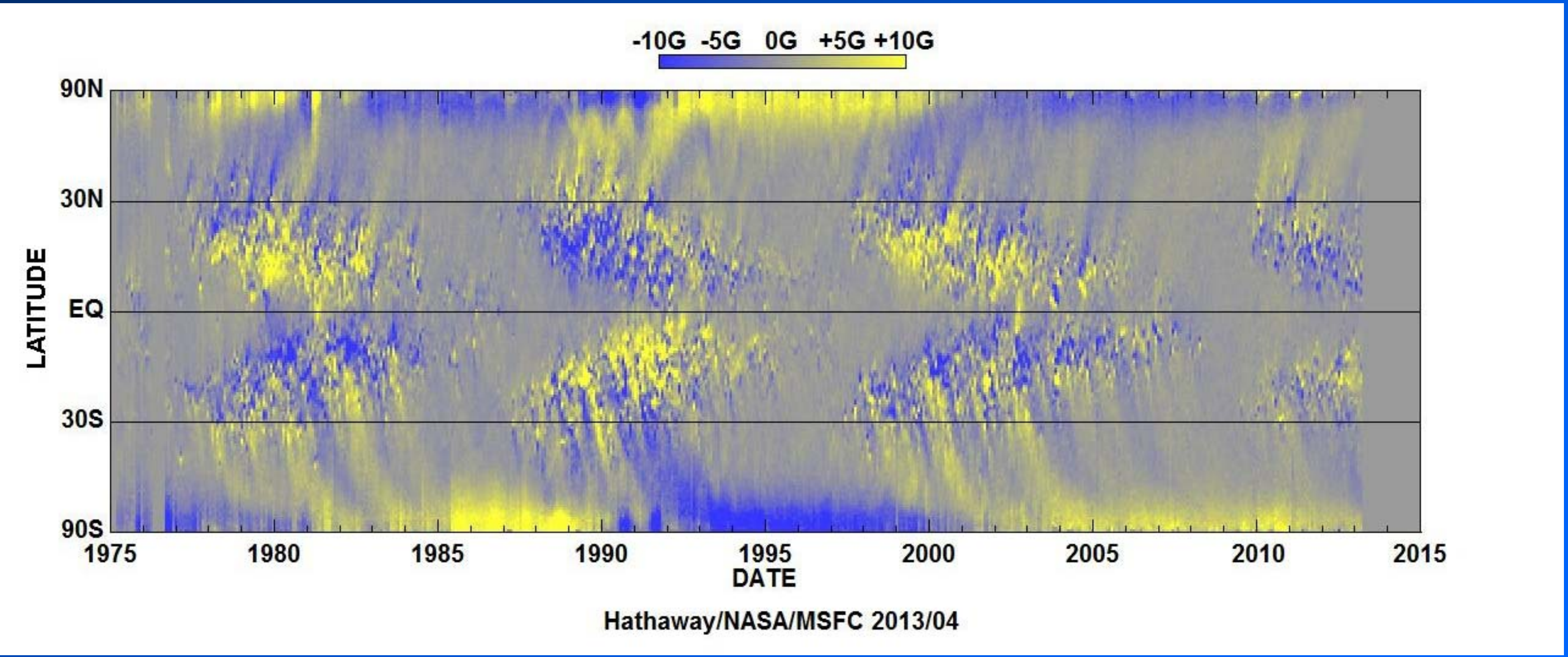
Flux Emergence

Magnetic flux emerges in the low-latitude active regions with Joy's Law tilt – leading polarity closer to the equator than the opposite, following polarity. The following (high-latitude) polarity in each hemisphere has the opposite sign of the polar fields established at the start of the cycle.



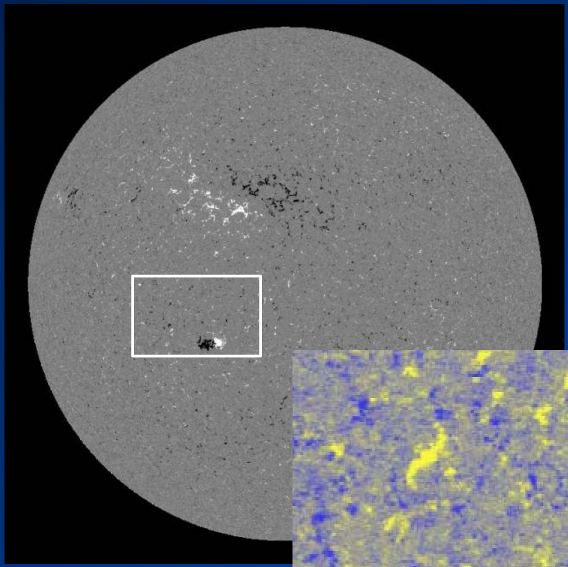
Flux Transport and Polar Fields

New regions emerge at lower and lower latitudes. Following polarity cancels the leading polarity that previously occupied that latitude band. The following polarity that remains at higher latitudes is transported to the poles where it reverses the old polar fields and builds up the new cycle polar fields.



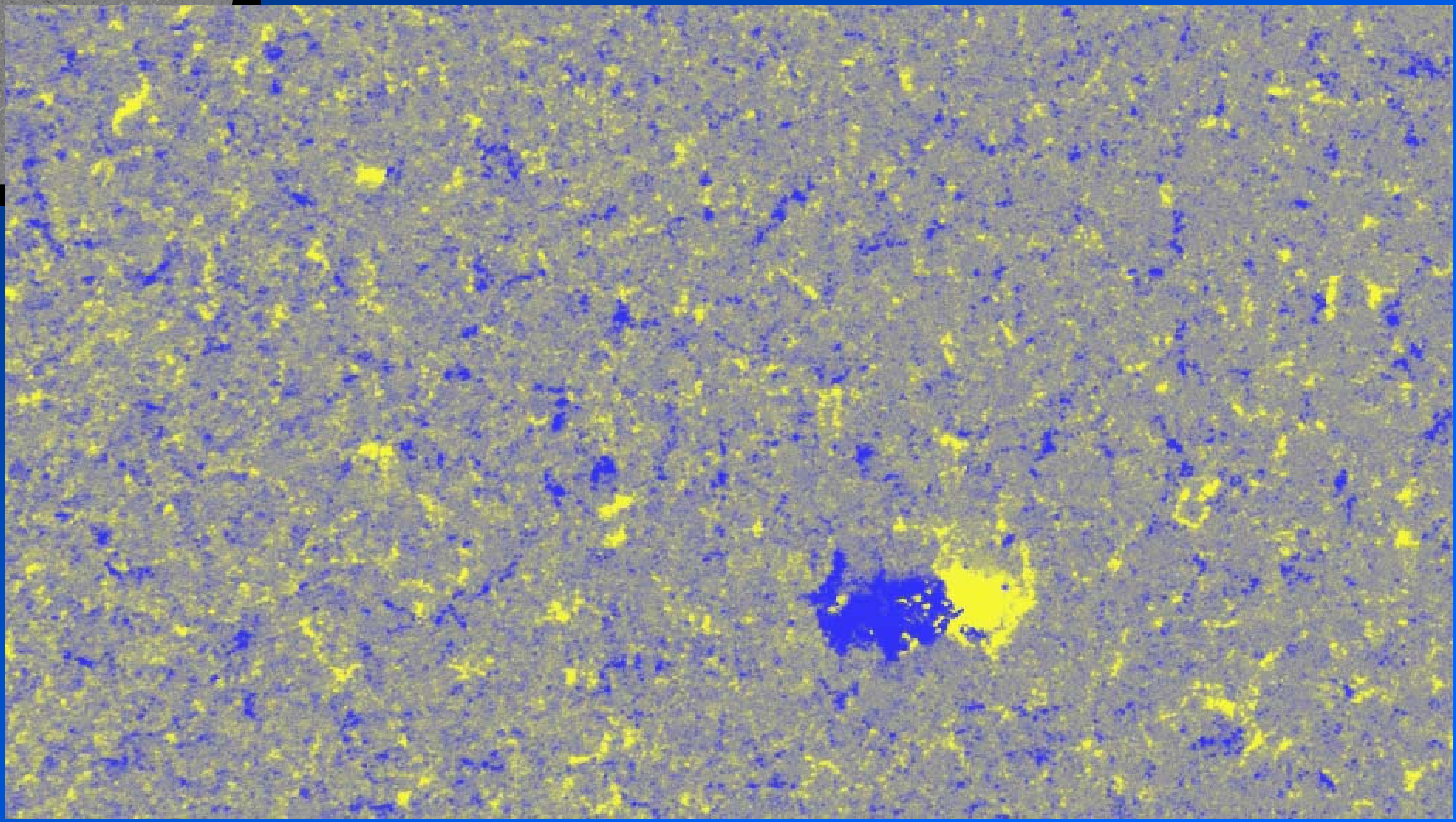
The variable strength of the polar fields can depend upon variations in the active region sources and/or variations in the flux transport processes.

Flux Transport



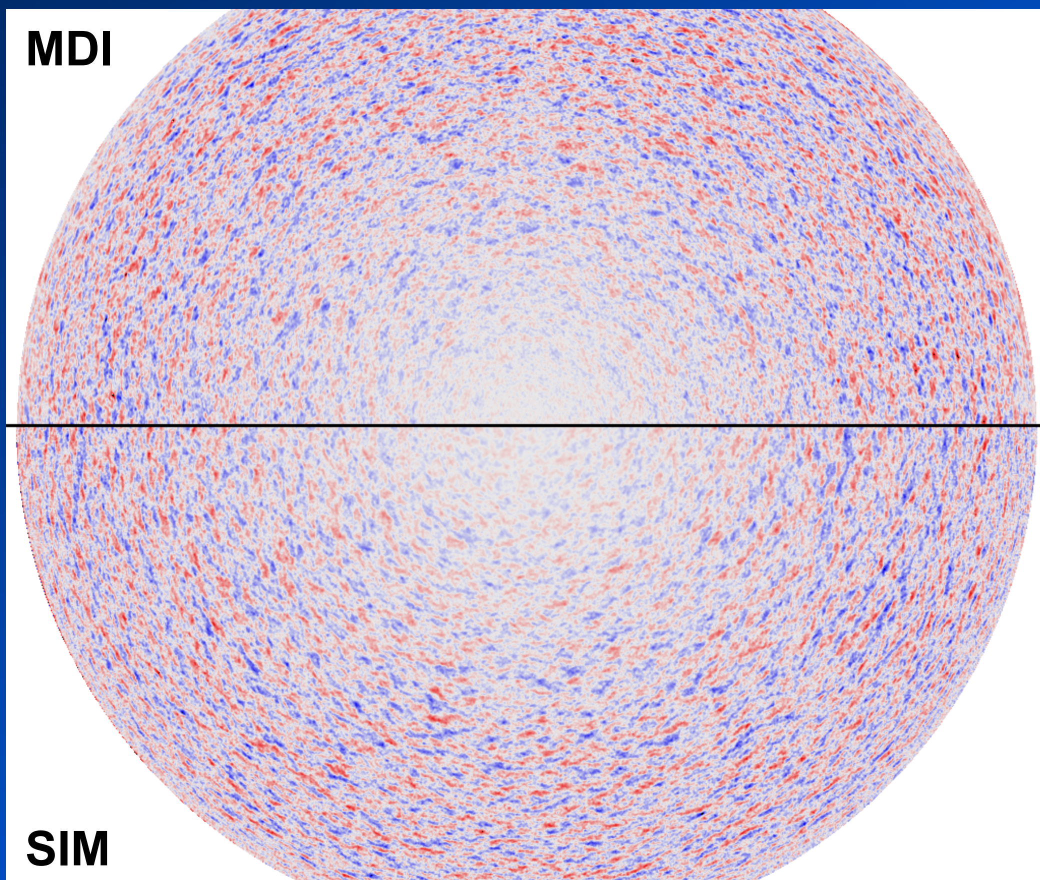
Convective motions (supergranules) quickly carry magnetic elements to their boundaries where they then move more slowly as the boundaries evolve.

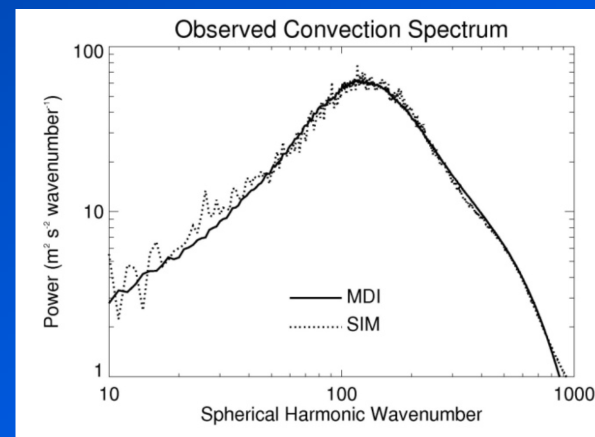
Four days from HMI.

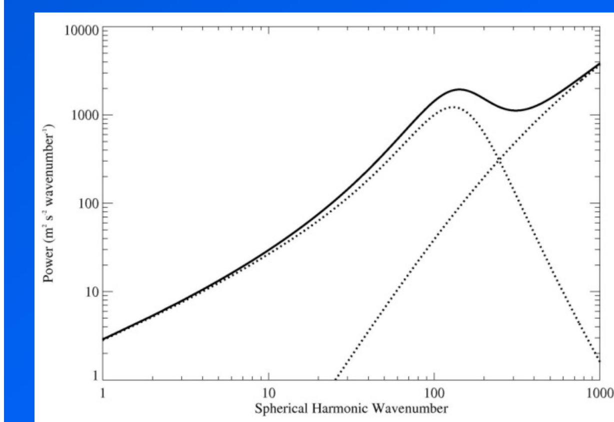


Supergranules

Hathaway et al. (2000, 2006, 2008, 2010) analyzed and simulated Doppler velocity data from MDI. The simulation uses an evolving spectrum of spherical harmonics that reproduce the observed velocity spectrum, the cell lifetimes, and the cell motions in longitude and latitude.

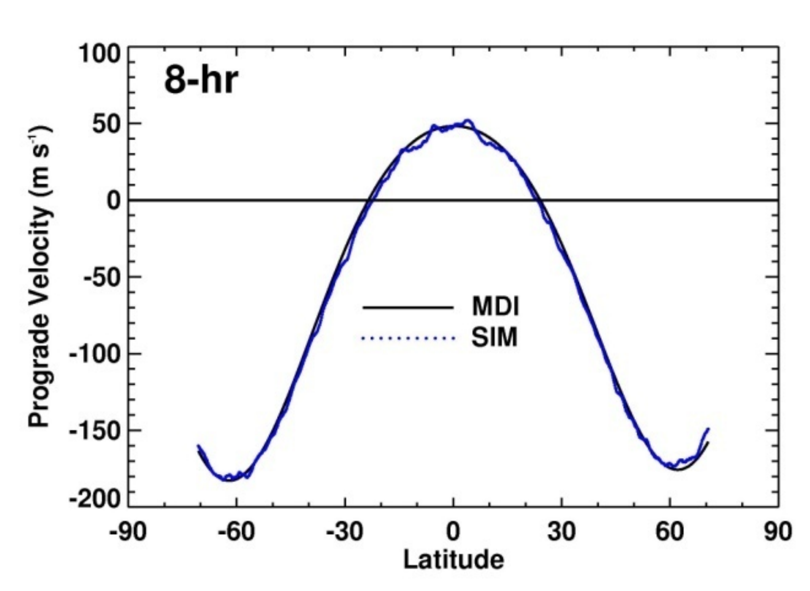




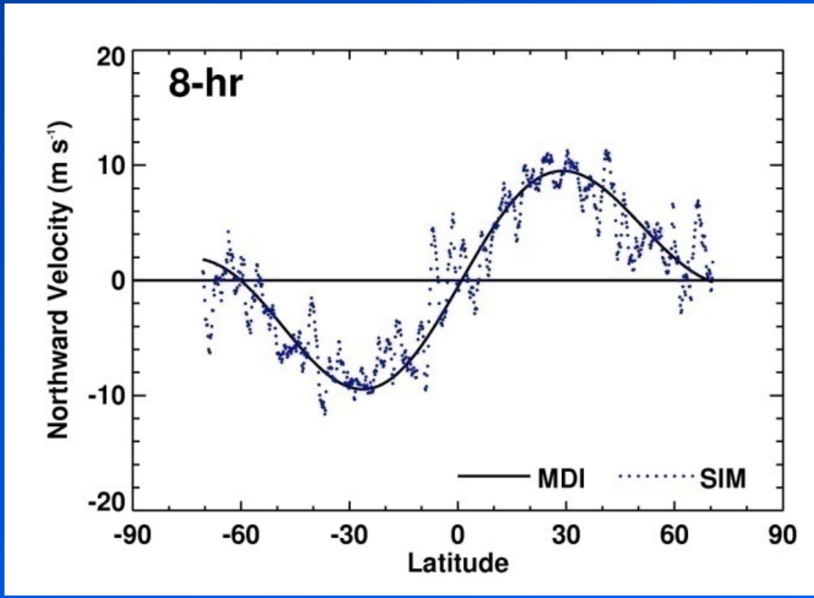


Axisymmetric Motions

Hathaway et al. (2010) and Hathaway (2012a, 2012b) measured and simulated the longitudinal and latitudinal motions of the supergranule pattern.



Supergranule pattern differential rotation profile May-July 1996.

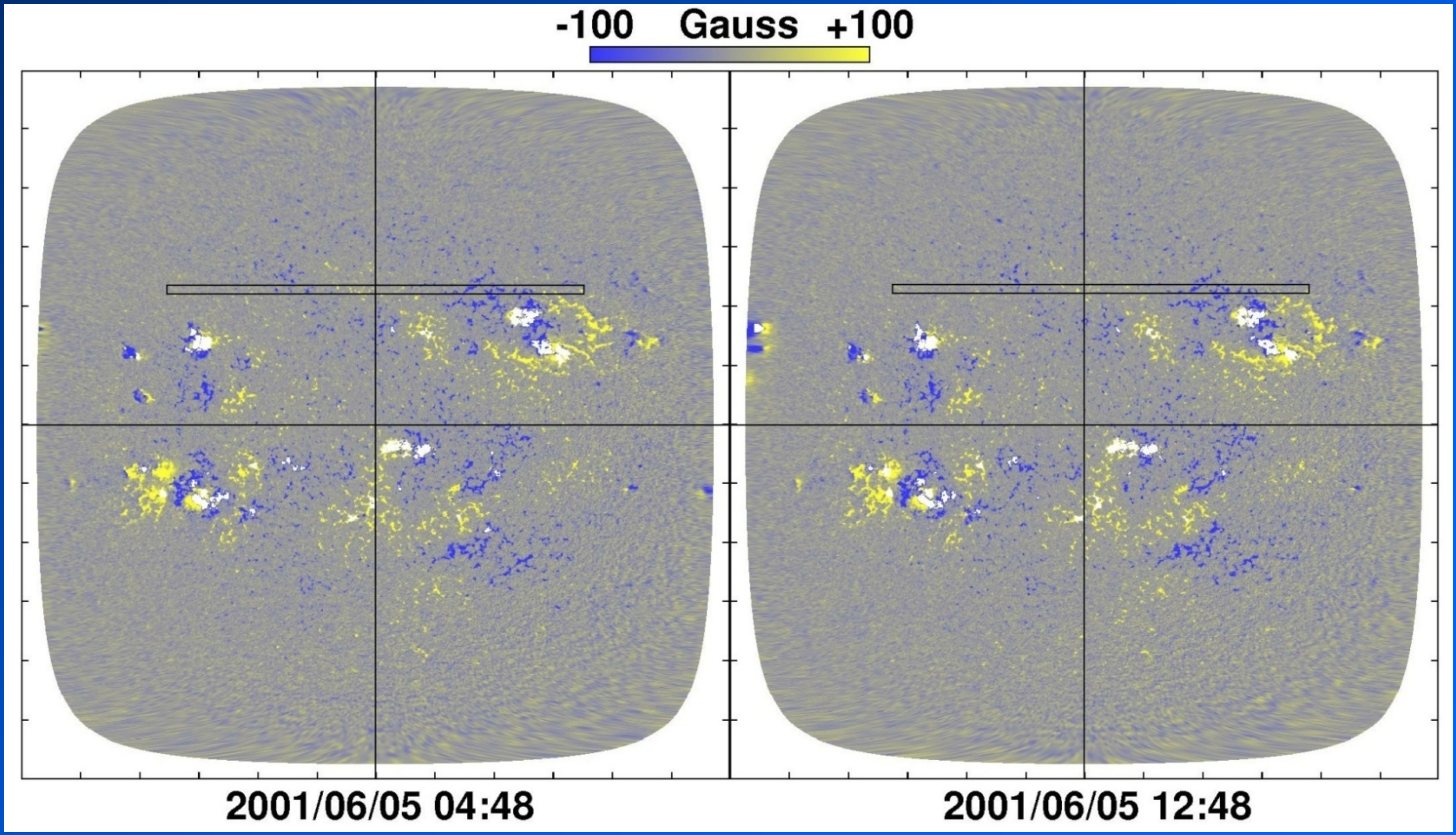


Supergranule pattern meridional flow profile May-July 1996.

As the supergranules themselves are advected by these larger flows they carry the magnetic elements at their boundaries and impart to them this differential rotation and meridional flow (Hathaway & Upton 2013).

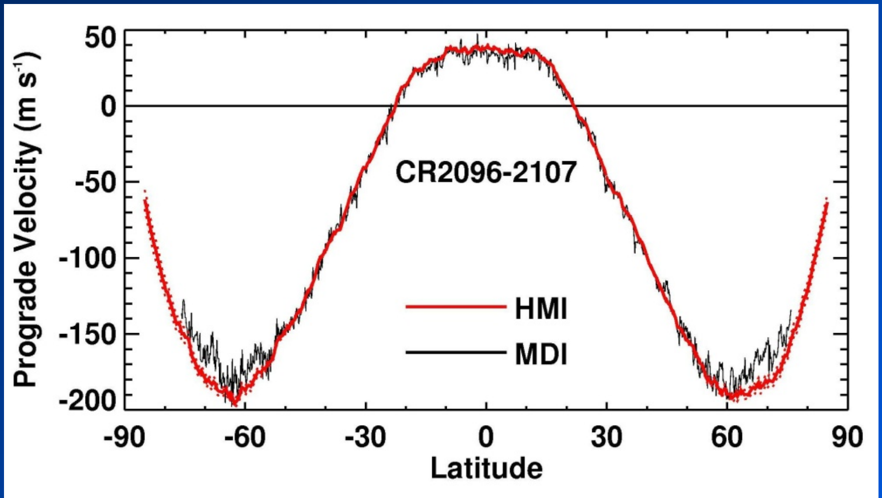
Magnetic Element Motions

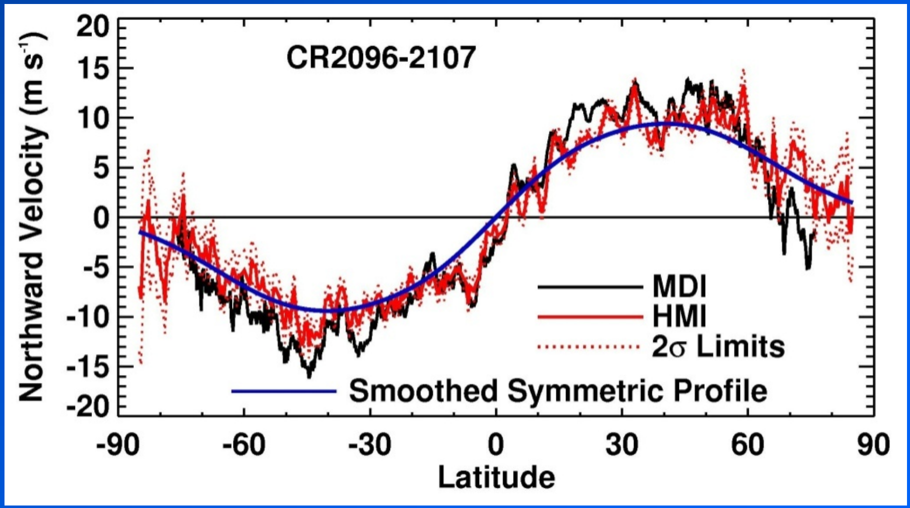
Hathaway & Rightmire (2010, 2011) measured the axisymmetric transport of magnetic flux by cross-correlating 11x600 pixel strips at 860 latitude positions between ±75° from 60,000 magnetic images acquired at 96-minute intervals by MDI on SOHO.



Axisymmetric Flow Profiles

Rightmire-Upton, Hathaway, & Kosak (2012) extended the measurements to HMI data and compared the results to the MDI measurements. The flow profiles are in good agreement but with small, significant, differences – DR is faster in HMI, MF is slower in HMI.





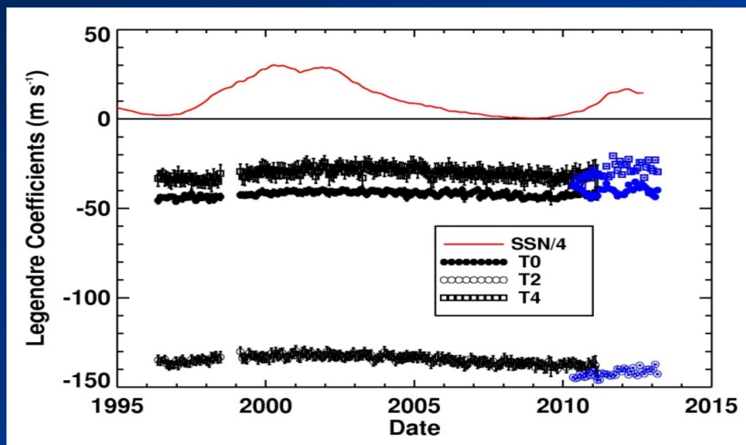
The average Differential Rotation profiles with 2σ error limits for the MDI/HMI overlap interval.

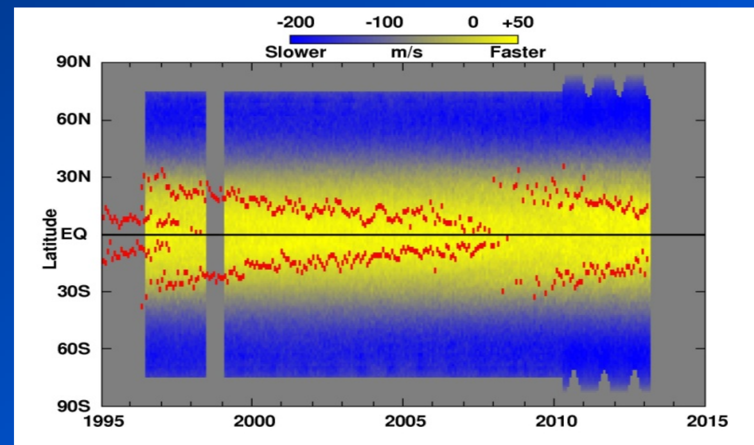
The average Meridional Flow profiles with 2σ error limits for the MDI/HMI overlap interval.

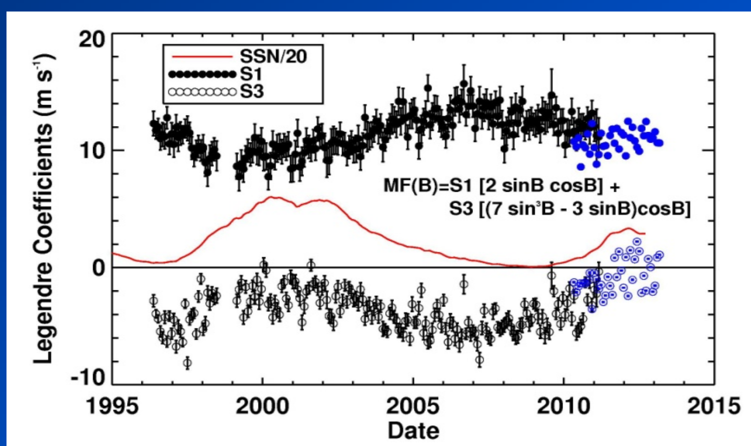
These profiles can be well fit with 4th order polynomials in sin(latitude).

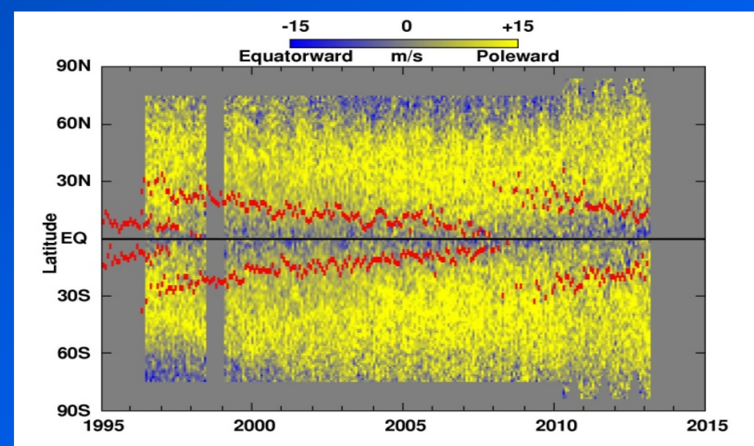
Flow Profile Histories

Differential Rotation hardly changes. Meridional Flow changes substantially!





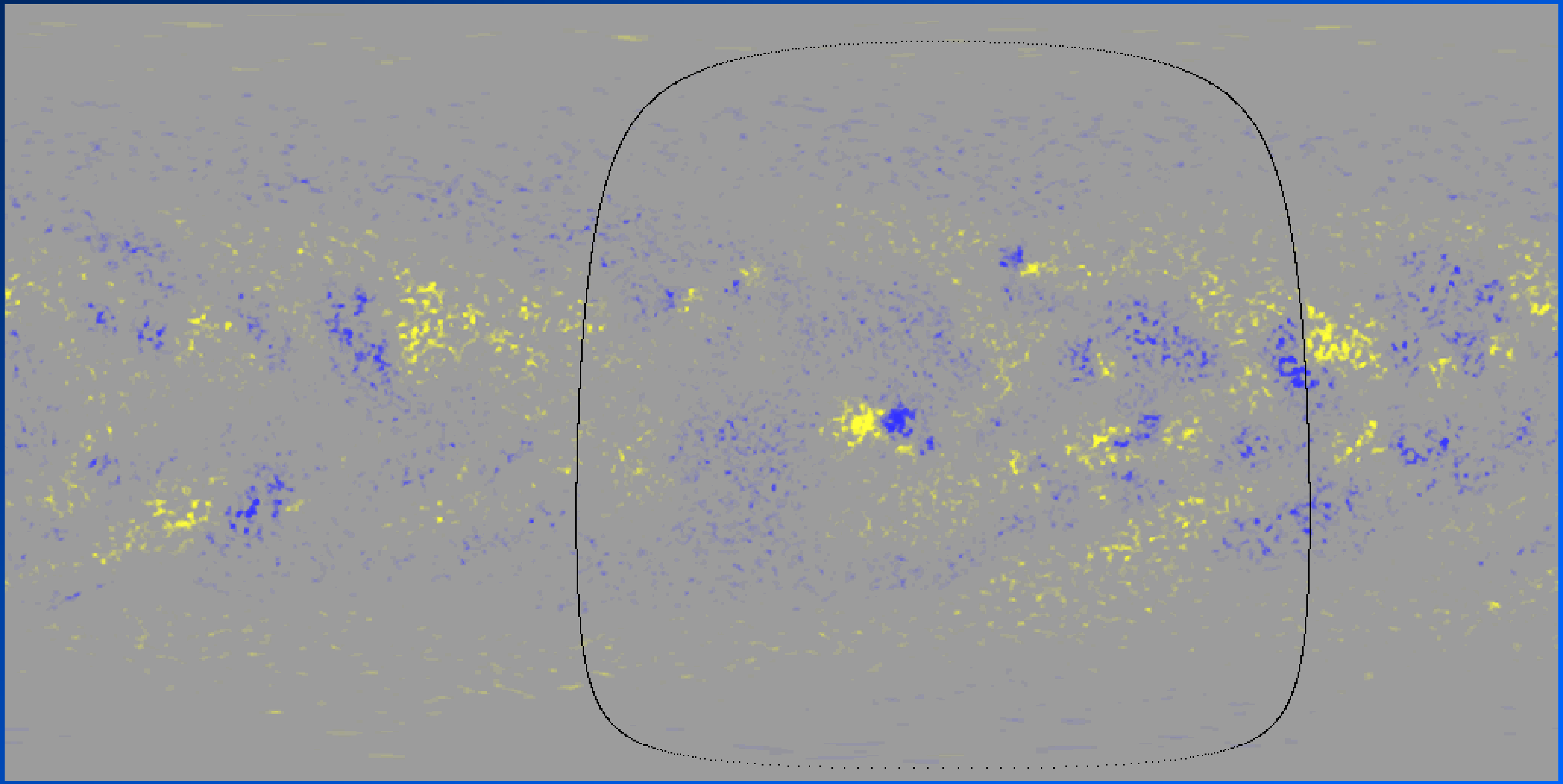




The Meridional Flow at Cycle 24 minimum was ~20% faster than it was at Cycle 23 minimum. A fast Meridional Flow produces weak polar fields in surface flux transport models (c.f. Wang, Robbrecht, & Sheeley, 2009).

Synchronic Maps

We are constructing 1024x512 Synchronic Maps every 15^{m} using evolving supergranules and the observed axisymmetric flows to transport flux with data assimilated from MDI and HMI at 96^{m} and 60^{m} intervals respectively.



Note that the flux elements are transported by the observed flows to the positions they are found when the data is assimilated.

Effects of Meridional Flow Variations (Upton's Thesis)

The Plan:

1. Produce a baseline set of synchronic maps assimilating data from all latitudes.
2. Produce a second set of synchronic maps assimilating data from the equatorial regions (active region sources) and using a constant, average, north/south symmetric meridional flow.
3. Produce a third set of synchronic maps assimilating data from the equatorial regions (active region sources) but using the observed and variable meridional flow.

This will quantify the effects of meridional flow variations on the polar fields in cycles 23 and 24.

The Problems:

1. Data from MDI and HMI have different magnetic sensitivities.
2. Data from MDI and HMI have image distortions
3. MDI did not produce data from June 1998 to February 1999

Conclusions

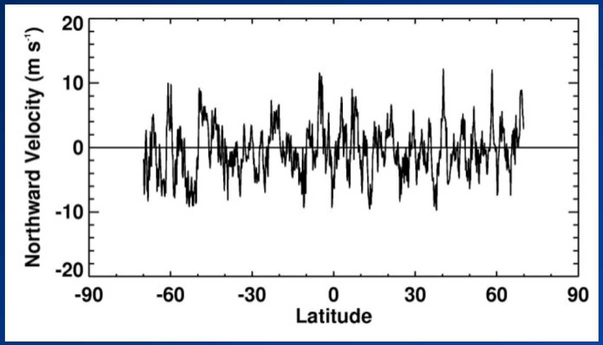
- The cause of this low minimum and long cycle can be attributed to the wimpy size of Cycle 24 itself.

- The cause of this wimpy cycle was the weak polar fields produced during Cycle 23.

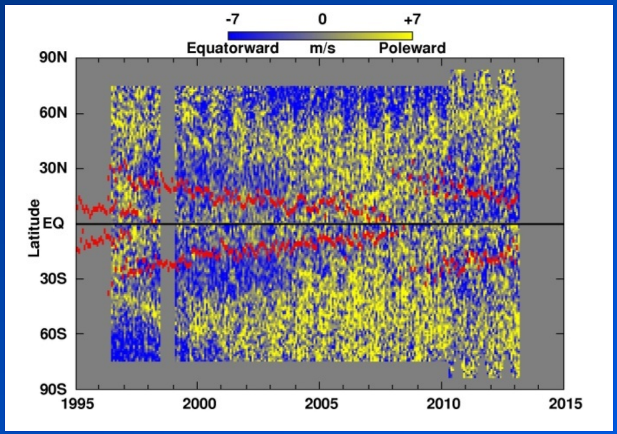
- The likely cause of the weak polar fields in Cycle 23 was the fast meridional flow late in the cycle (but this still needs to be quantified).

We gratefully acknowledge support from the CCMSC Program.

Our Meridional Flow Measurements are NOT Substantially Influenced by Supergranule "Diffusion"

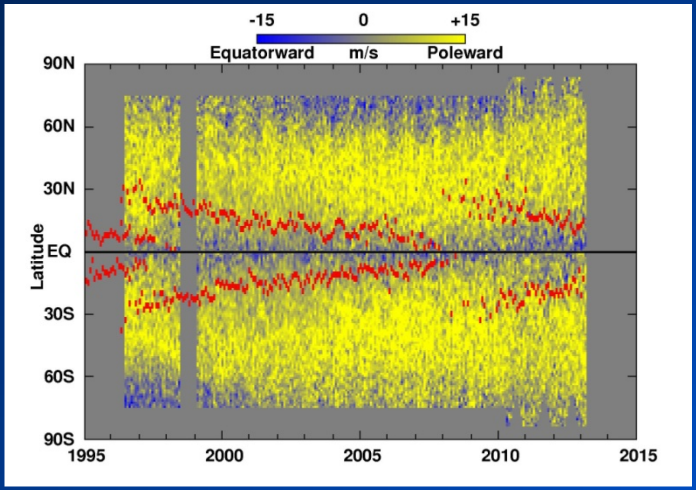


1. In Hathaway & Rightmire (2011) we found that NO measureable meridional flow signal was produced by evolving supergranules with observed properties advecting the magnetic field elements that produced an observed magnetic field map.

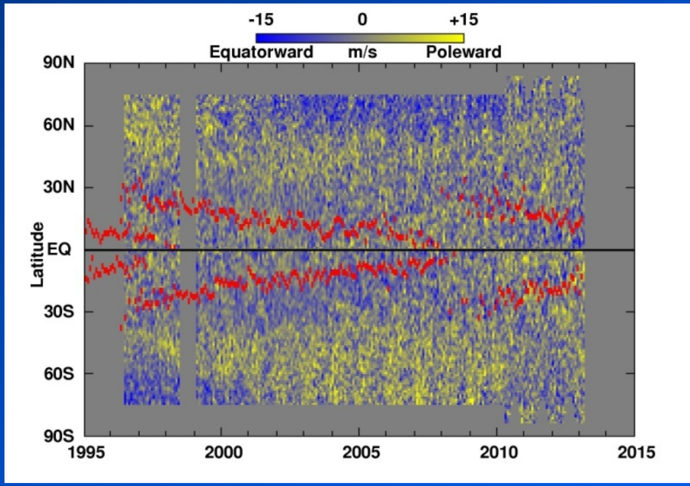


2. The observed effects of the active latitudes is a superimposed flow TOWARD the active latitudes not away as would be produced by diffusion.

Our Legendre Polynomial Coefficients DO Capture the Evolution of the Meridional Flow Pattern



Raw, individual meridional flow profiles since May of 1996.



Individual meridional flow profiles since May of 1996 with the Legendre Polynomial fits removed.